FRACTURE ENERGY OF WOOD AND ROOT BURL WOOD OF THUYA (*TETRACLINIS ARTICULATA*)

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EL ALAMI S, EL MOURIDI M, LAURENT T, CALCHERA G, FAMIRI A, HAKAM A, KABOUCHI B & GRIL J. 2013. Fracture energy of wood and root burl wood of thuya (*Tetraclinis articulata*). The fracture energy of wood and root burl wood of thuya was measured using a single-edge-notched specimen bending test method. The variations along the longitudinal (L) and transverse (T) directions were studied using specimens taken from one radial (R) section each of thuya wood and thuya burl. Thuya burl was more resistant than thuya wood to crack propagation in RL system (in the tangential plane). This difference is explained by the presence of outgrowths, composed of cells with thicker walls that make the burl wood usually denser than thuya wood which was consistent with the radial orientation of the outgrowths. The decrease of fracture energy along the longitudinal direction was explained by the progressive reduction of outgrowths concentration.

Keywords: Mode I, single-edge-notched bending specimen, outgrowths, TL and RL systems

EL ALAMI S, EL MOURIDI M, LAURENT T, CALCHERA G, FAMIRI A, HAKAM A, KABOUCHI B & GRIL J. 2013. Tenaga rekahan kayu dan kayu pepusar akar *Tetraclinis articulata*. Tenaga rekahan kayu dan kayu pepusar akar *Tetraclinis articulata* disukat menggunakan ujian lentur spesimen tertakuk pinggir tunggal. Variasi sepanjang arah membujur (L) dan melintang (T) dikaji menggunakan spesimen yang diambil daripada satu bahagian arah jejari (R) masing-masing daripada kayu *T. articulata* dan pepusar akarnya. Pepusar akar *T. articulata* lebih tahan terhadap perambatan retak dalam sistem RL (dalam satah tangen) berbanding dengan kayunya. Perbezaan perambatan retak disebabkan oleh kehadiran ketumbuhan yang terdiri daripada sel berdinding lebih tebal yang menjadikan kayu pepusar *T. articulata* biasanya lebih tumpat berbanding dengan kayunya. Perbezaan ini juga selari dengan orientasi jejari ketumbuhan. Tenaga rekahan yang berkurangan sepanjang arah membujur disebabkan oleh kepadatan ketumbuhan yang kian menurun.

INTRODUCTION

Fracture energy in mode I, denoted $G_{f,I}$, is the mechanical energy required to produce complete rupture in the opening mode of a pre-split sample, divided by the ruptured surface (Baillères 1994, Gustafsson & Larsen 1990). This parameter, measured in N m^{-1}, is used to characterise the ability of a material to withstand crack propagation. It is, in principle, an intrinsic property that enables the optimum choice of material for a specific application and provides an understanding of its performance in service.

The materials used in this study were thuya (*Tetraclinis articulata*) wood and thuya root burl wood (simply referred to as thuya burl hereafter). Thuya burl is an outgrowth developing underground on the root of the thuya tree under poorly understood conditions. Its wood is prized by craftsmen for inlay work, cabinet making and production of various items which play an important socioeconomic role for meeting local needs of neighbouring populations. Published studies concerning the thuya tree pertain

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mainly to its development and phytoecology (Fennane et al. 1984, Fennane 1987), drying of its wood (Lmouchter 2001), wood quality (Dakak 2002) and attacks by fungi (Abbas et al. 2006). Recently, a study was conducted on the physical characterisation of thuya burl (El-Mouridi et al 2011). No study on the fracture energy of thuya wood or thuya burl has been undertaken. This information could be used to optimise the cutting processes used by craftsmen. The purpose of this study was to determine the fracture energy within a disc of thuya burl and to compare it with that of thuya wood.

MATERIALS AND METHODS

Sampling and cuts

The raw materials (thuya log of approximately 1 m in length and a whole thuya burl) used in this study was obtained from Ait Daoued forest in the province of Essaouira by the Moroccan High Commission for Water and Forests. Consequently, we have no guarantees that the wood and the burl were obtained from the same tree. Sawing was performed at the Physical and Mechanical Test Laboratory of the Forestry Research Center in Rabat, Morocco. Samples were cut and tested at the French Agricultural Research Centre for International Development (CIRAD), Montpellier, France.

The thuya burl was divided into two twin sections, sawn through a longitudinal plane (Figure 1a). Two central sections, M1 and M2 (Figure 1b), were set aside for the fracture energy test. They were identified by three directions, namely, L which corresponded to the longitudinal direction of the tree trunk, as well as R and T which defined the transverse plane to this axis. To correctly understand the directional identification of the samples that were used in this study, we analysed the choice of directions (R, T, L) conventionally used for wood. A transverse section of thuya, perpendicular to the main direction of the trunk (Figure 2a) clearly identifies the radial and tangential directions from growth ring orientation. In thuya burl, on the other hand, a transverse section (Figure 2b) does not display the same symmetries. This secondary or radial growth is, in part, modified by the presence of darker outgrowths, specific to thuya burl, with symmetries similar to those of the wood, but at the local level. Thus, we kept the usual notations (L, R, T) for thuya burl, with R and T indices corresponding respectively to disc width and thickness. We traced a grid on disc M1 to create test pieces of dimensions 12 mm 20 mm × 20 mm (R × T × L), taking the saw kerf into account.

Thuya burl samples were marked according to a Bij row–column grid notation, where B and W = name of the studied wood (B for thuya burl and W for thuya wood), i = ith row and j, =

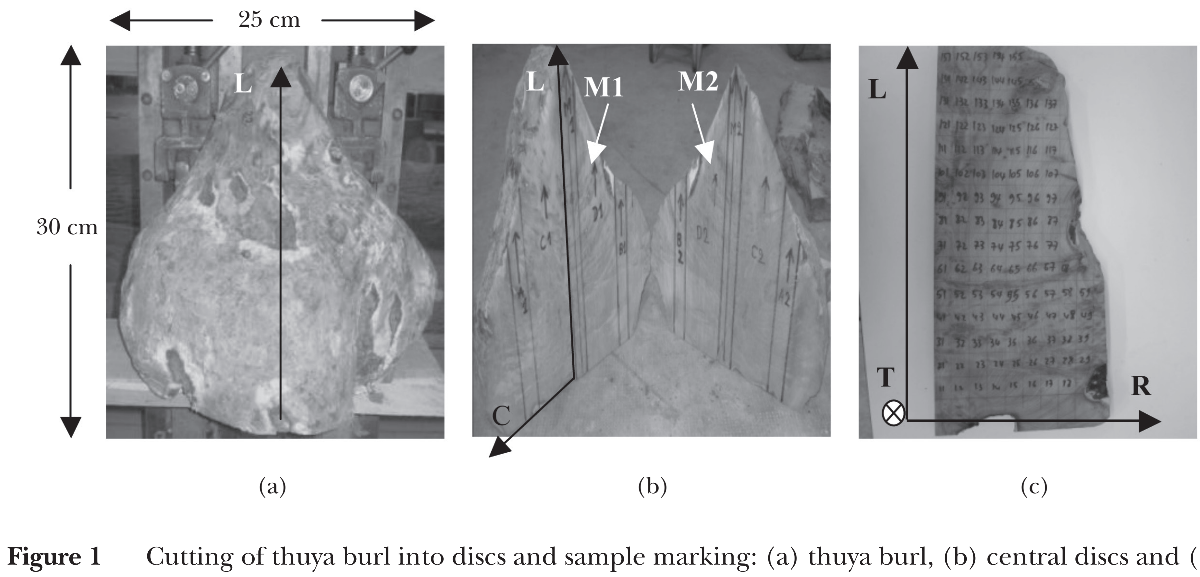


Figure 1 Cutting of thuya burl into discs and sample marking: (a) thuya burl, (b) central discs and (c) disc M1, planed and traced

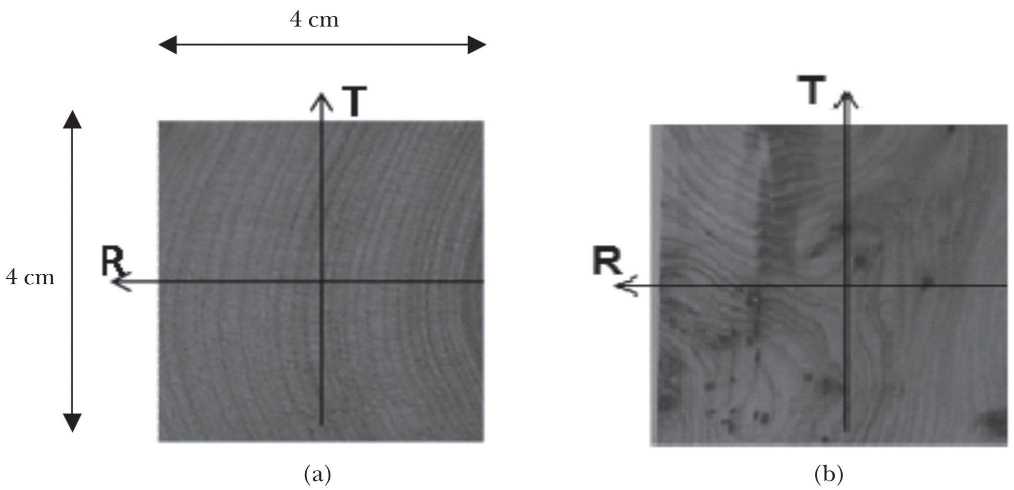


Figure 2 Cross-section of (a) thuya wood and (b) thuya burl

j^{th} column. Row 1 was at the bottom of the disc and column 1, the column coinciding with the first longitudinal sawing plane of the burl (Figures 1c and 3). The coordinates (X_{ij}, Y_{ij}) of the centre of each disc test piece (Figure 3) were determined by the following equations:

$$Xij = a\ (j - 0.5) + (j-1)\ e \quad ; \quad Yij = b\ (i - 0.5) + (i-1)\ e \qquad (1)$$

where a and b = width and height of the sample respectively and e = thickness of the saw kerf, measured at 3.5 mm. The thuya wood log was cut into slabs. Only the central section, 20 mm thick, was kept. It was divided into two parts along its longitudinal axis passing through the pith, then traced and marked in the same manner as that used for the thuya burl. These parallelepipeds were used as the central part of single-edge-notched bending specimens. The procedure developed was used to estimate fracture energy of wood in mode I of crack propagation (Gustafsson & Larsen 1990) and detailed below.

Test arms were glued onto discs using polyvinyl adhesive, allowing repositioning during the first few minutes (Figure 4a). The system was clamped for at least 24 hours (Figure 4b). The arms were made from goupil wood, selected for its high rigidity that allowed neglecting their contribution to the elastic energy during bending test. Once the discs had been glued and stabilised, they were sawn twice to obtain test pieces of 20 mm × 12 mm × 140 mm (Figure 5). To avoid unstable crack propagation, an initial crack length of 12 mm (60% of the beam depth) was cut into each test piece along the greatest length of the section using a 1.5-mm thick special circular saw (Daudeville 1999). The system of crack propagation was described by two letters AB, where A specified the direction perpendicular to the plane of the crack (the axial direction of the central portion of the specimen) and B, the expected direction of crack propagation (the height of the specimen) (Smith et al. 2003). TL and RL crack propagation systems are the most frequently used because of the particular design of timber structures. In this study, fracture energy measurements were conducted on 81 thuya wood specimens prepared for TL system and on 137 thuya burl specimens (88 prepared for TL system and 49 for RL system), as illustrated in Figure 6.

Measurement of moisture content and density

The moisture content and density measurements were performed for each section on 8 mm × 12 mm × 20 mm test pieces after fracture energy tests. The test pieces comprised 25 thuya wood and 27 thuya burl. Weight was measured using a precision balance with a resolution of 0.001 g and the dimensions at three reference directions were measured using a digital comparator with resolution of 0.001 mm.

Measurement of fracture energy

The experimental system consisted of an electromechanical universal testing machine fitted with a force gauge with maximum capacity of 2000 N (at 0.1% of force reading) to induce fracture in mode I. The upper cross piece, equipped with a displacement transducer with resolution of 0.01 mm, was used to perform the three-point bending test. The test was programmed and controlled by a computer that was also used to acquire measurements using the TestWorks4 software. Two support balls, one a 25-mm diameter steel ball and another, a freely rotating 30-mm diameter roller, were used for the three-point bending test (Figure 7). With this assembly, we were able to correct possible parallelism problems between the side arms and central element (pre-cut test sample) and vertically align the 25-mm diameter central support ball and the cut. Growth irregularities would very easily provoke unwanted torsion load and result in mixed rupture mode. Indentation resulting from the use of steel balls and cylinder can cause very slight measured displacement but the amount is negligible.

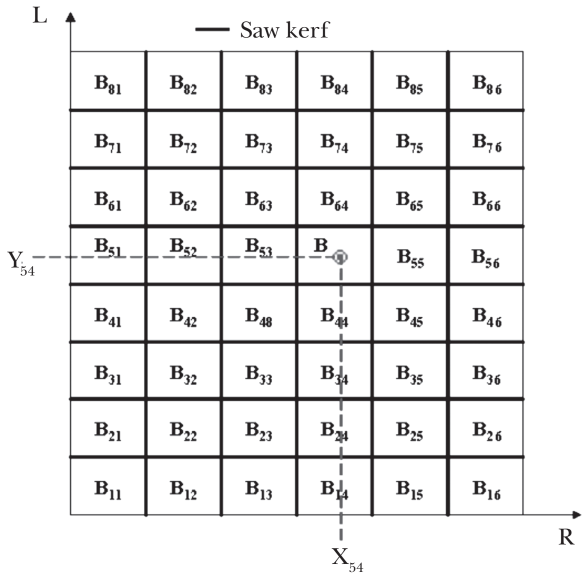
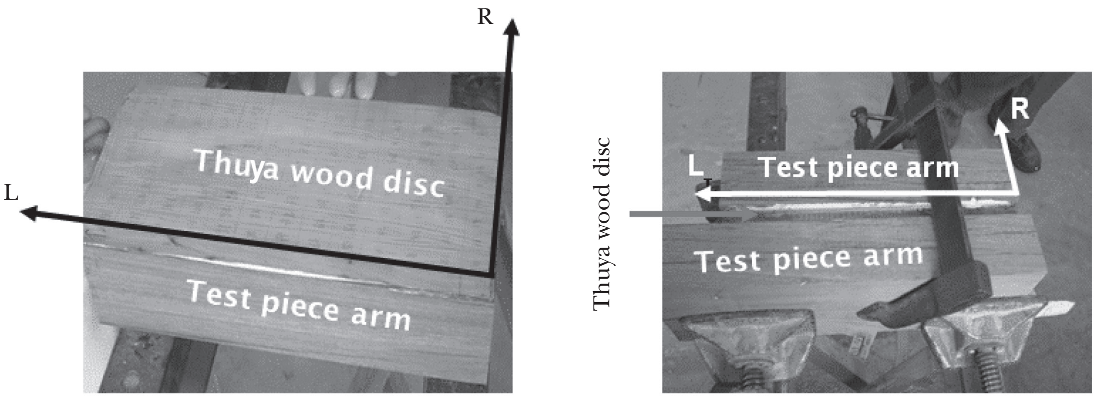


Figure 3 Marking of the centre of thuya burl M1 disc samples

The method described by Gustafsson and Larsen (1990) was used to measure fracture energy. Following a procedure proposed by Baillères (1994), preliminary tests were performed to determine the displacement speed of the load cell most appropriate for the type of wood. Speed was increased from 0.5 mm min^{-1} at the start of the test to 2 and 8 mm min^{-1} after 3 and 5 min respectively. These velocities were determined so that the shape of the force–displacement curve (Figure 8) was similar to the curve obtained by Gustafsson and Larsen (1990). The test was stopped once fracture was complete. The displacement was measured using linear variable differential transducers (± 2.5 mm) in contact with a reference surface rigidly attached to the load application device. Force and displacement values were recorded every 0.1 s. Fracture energy $G_{f,I}$ was calculated as the



(a) (b)

Figure 4 Disc arm bonding: (a) gluing an arm and (b) clamping thuya wood; R = radial, L = longitudinal

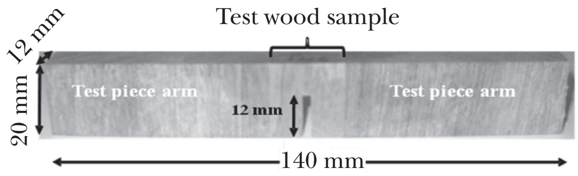


Figure 5 Specimen for fracture energy test

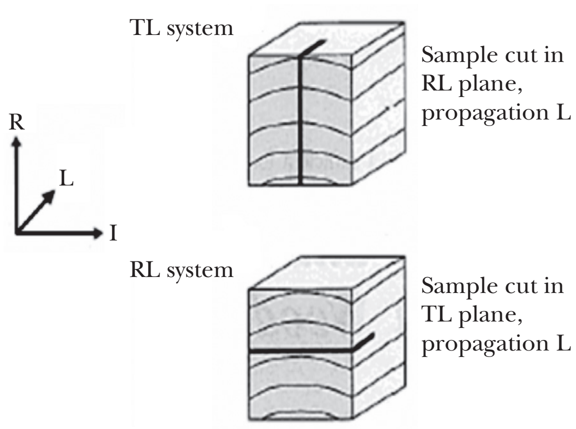


Figure 6 Sample cuts and fracture system notation (illustrated for thuya wood); R = radial, L = longitudinal, T = transverse

sum of work performed by the central support and by the dead weight of the test piece relative to the area of the fractured surface:

$$G_{f,I} = \frac{1}{S}\ mg.\ \delta_0 + \int_0^{\delta_0} F.d\delta \qquad (2)$$

where δ_0 = displacement recorded from the start of loading until complete fracture, S = theoretical (nominal) fractured ligament area, mg = test piece weight and F = force recorded during the test.

It should be noted that although the test was intended to measure a material property, the value obtained was not intrinsic to the material due to the existence of a damaged zone in front of the tip of the crack (process zone). This caused scale effects that cannot be quantified. However, the value can be used to compare inter-material and inter-directions.

To study the correlations between density and sample position within the disc, we performed a statistical analysis (general linear model) of the oven-dry density values for thuya wood and burl. Three variables were studied in this analysis: position variables X_L and X_R and coupling between both variables, X_LX_R. Thuya wood and thuya burl density is expressed as follows:

$$D_0^K = a_K + b_K X_L + c_K X_R + d_K X_L X_R + \varepsilon \qquad (3)$$

where K = data relative to thuya burl (B) or wood (W), a_K, b_K, c_K, d_K = linear regression coefficients and ε = standard error.

RESULTS AND DISCUSSION

Density and moisture content

The density and moisture content values for thuya wood and thuya burl, obtained from the test pieces are presented in Table 1. The moisture contents of the test pieces were 8.88 ± 0.15% for thuya wood and of 12.2 ± 0.4% for thuya burl. Thuya burl is dense and comprises dark-coloured, high-density outgrowths encased in a matrix of ligneous tissue with a density comparable with that of thuya wood (El-Mouridi et al. 2011). The small sample size used to determine density and moisture content meant that these samples contained few or no outgrowths, thus explaining the similar values obtained for both thuya wood and thuya burl.

Results of the study of correlation between density and sample position are presented in Table 2 which provides estimated values, along with p value of the regression coefficients of equation (3). It was observed that for thuya burl, there was no significant correlation between density and the X_L, X_R or X_LX_R coupling variables ($p > 5\%$). For thuya wood, on the other hand, a dependency between the X_R and X_LX_R variables was observed, corresponding to the juvenile transition from pith to periphery (Dakak 2002). This was confirmed by a second regression analysis where $b_W = 0$ was assumed in equation 3.

Fracture energy in TL system

Fracture energy in thuya wood and thuya burl increased with increase in density (Figure 9); the denser the material, the greater its resistance to crack propagation. Fracture

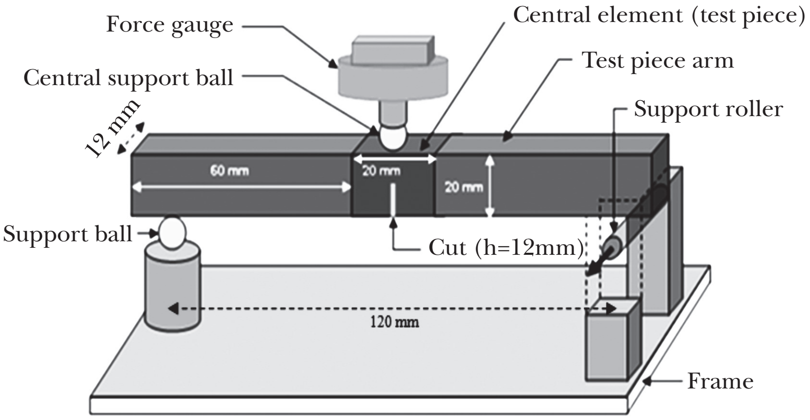


Figure 7 Experimental system: three-points bending set-up

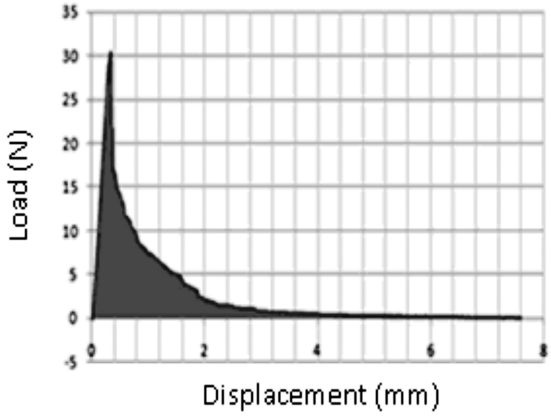


Figure 8 Force–displacement curve for thuya wood in TL system

energy in thuya burl TL system ranged from 325 to 1736 N m^{-1} and showed high degree of variability in the longitudinal (Figure 10a) and transverse directions (Figure 10b). In addition to the influence of fracture surface roughness (Morel et al. 2003), this result can be explained by the presence of outgrowths that increase rigidity or give a higher degree of heterogeneity in thuya burl.

Fracture energy in thuya wood ranged from 89 to 435 N m^{-1} (Figure 10). Thuya wood displayed lower variability in facture energy compared with thuya burl in the studied directions. The lower variability can be explained by the organisation of the internal structure (radial, transverse and longitudinal material symmetries) of the wood with low intra-ring heterogeneity (Dakak 2002). The lack of outgrowths renders the wood more homogeneous than thuya burl.

From the results obtained, we conclude that thuya burl is tougher than thuya wood in TL system. *Eucalyptus camaldulensis* had mean fracture energy of 325 N m^{-1} (Maziri et al. 2010). In another study, it was reported that various *Eucalyptus* clones tested with the same geometry but in the green state had fracture energy of 140 to 295 N m^{-1} with large variations related to radial position or the presence of tension wood (Baillères 1994). Fracture energy values for larger dimensions *Pinus pinaster* and *Picea abies* were 330 and 150 N m^{-1} respectively (Dourado et al. 2008). Thus, it was concluded that fracture energy of thuya wood was in the usual range of values observed for other hardwood species of similar density, while thuya burl was definitely tougher.

It was also observed that fracture energy for thuya burl decreased from bottom to top of the M1 disc, the top having similar value to that of thuya wood. This variation is closely linked to outgrowth concentration of thuya burl that decreases longitudinally (El Mouridi et al. 2011). The upper part of the thuya burl section possesses an intermediate structure between thuya burl and wood. It is a transition zone between the inner structure disrupted by outgrowths of thuya burl and the more organised structure of thuya wood.

Fracture energy in RL system

Fracture energy test in RL system for thuya wood and thuya burl showed high degree of variability in the L (Figure 11a) and R directions (Figure 11b). The energy values obtained showed a decrease in the vertical direction of the studied disc. Minimum fracture energy for M2 thuya burl disc was 598.5 N m^{-1} while the maximum, 4323.6 N m^{-1}. These high values can be related to the heterogeneity of the thuya burl. The concentration gradient and orientation of outgrowths in thuya burl caused rough crack surface. Generally, crack growth was stable and its spread often took place in the expected plane with a small deviation. However, it was obvious that the orientation of the outgrowths was the major factor that influences rupture of thuya burl.

Table 1 Moisture content and density of thuya wood and burl

Parameter	Wood	Minimum	Maximum	Mean
Moisture content (%)	Thuya burl	4.45	14.98	12.20 ± 0.40
	Thuya	8.35	9.59	8.88 ± 0.15
D_H (g cm^{-3})	Thuya burl	0.66	0.95	0.841 ± 0.027
	Thuya	0.78	0.95	0.835 ± 0.018
D_0^K (g cm^{-3})	Thuya burl	0.62	0.90	0.791 ± 0.028
	Thuya	0.73	0.90	0.789 ± 0.017

D_H = density at moisture content 8.88 ± 0.15% for thuya wood and of 12.2 ± 0.4% for thuya burl, D_0^K = oven-dry density

Fracture energy was higher in the RL system which might be explained by the fact that in RL system, fracture occurred in a plane perpendicular to the axial direction of the outgrowths. Moreover, during tests, it was noted that the parts on either side of the cut did not separate perfectly. The two arms frequently remained joined by twisted filaments. Results also showed a gradient of fracture energy in the X_R direction. This can be explained by the fact that new outgrowths appear with distance from the core of the burl. Thus, their number increases from the centre outwards and, consequently, the fracture energy transversal to outgrowths in RL system increases.

Burl fracture energy in TL and RL systems

Fracture energy in TL and RL systems of thuya burl showed a high degree of variability which also decreased in the longitudinal direction. Fracture energy values were higher in the RL system. Nevertheless, it was noted that the area fractured in RL system was higher than in TL system due particularly to the transverse orientation of the outgrowths, leading to a curved or even rippled fracture surface.

This result has direct impact on the manner in which thuya wood is cut by craftsmen. It is easier to cut thuya wood in the radial plane (TL

Table 2 Estimate values and p values of the regression coefficients between oven-dry density and position within the disc

Coefficient (variable)	Thuya burl		Thuya wood		Thuya wood (regression analysis with $b_W = 0$)	
	Estimated value	p value (%)	Estimated value	p value (%)	Estimated value	p value (%)
a (g cm^{-3})	0.78	-	0.76	-	0.75	-
b (X_L) (g cm^{-4})	0.00032	15.7	-0.00011	22.9	(0)	-
c (X_R) (g cm^{-4})	0.000052	92	0.0013	0.00003	0.00146	6×10^{-6}
d ($X_L X_R$) (g cm^{-5})	-0.0000045	15.4	-0.0000035	0.36	-0.0000047	10^{-9}

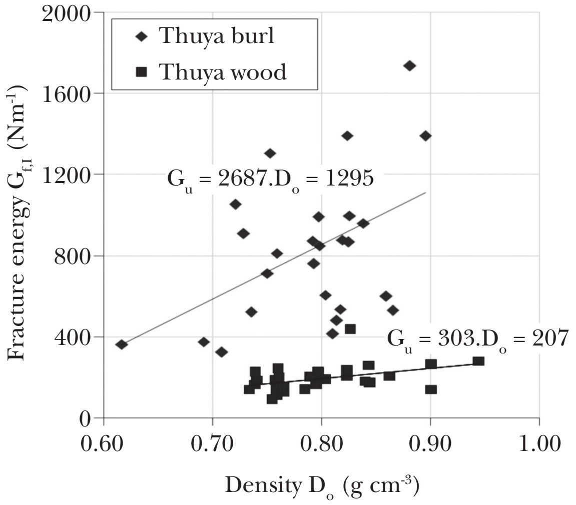


Figure 9 Relation between fracture energy and oven-dry density

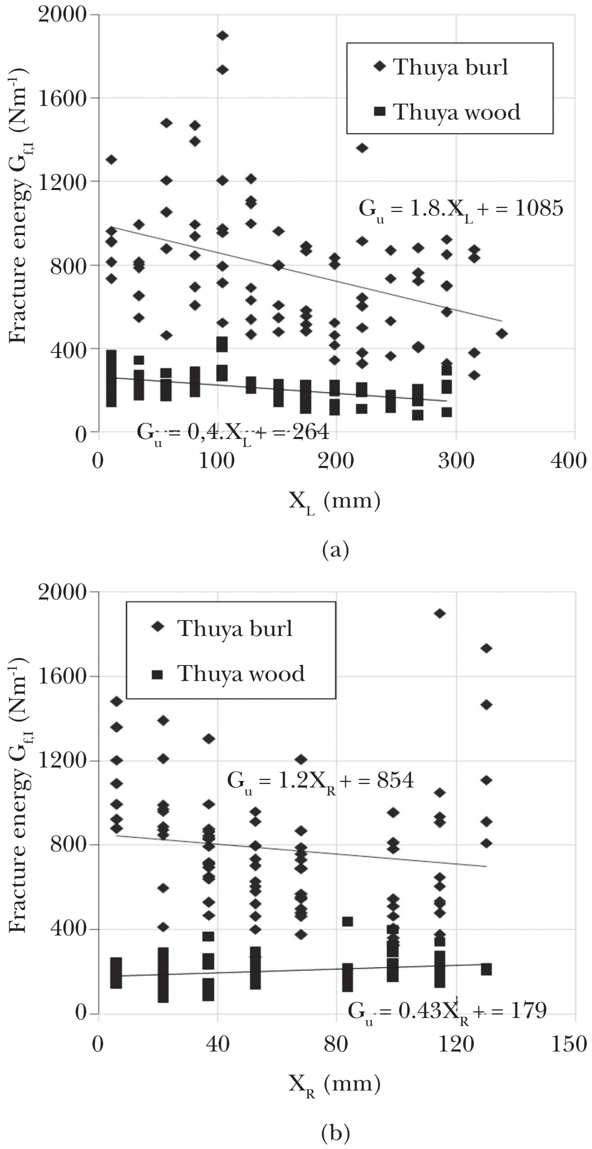


Figure 10 Fracture energy in TL system of thuya burl and thuya wood: variation along (a) L and (b) R directions

system) than the tangential plane (RL system). The aesthetic appearance is preserved in both modes.

CONCLUSIONS

From the fracture energy values of thuya wood in TL system and thuya burl in TL and RL systems, we conclude that the latter is tougher in TL system. Unlike thuya wood, thuya burl displayed a high degree of density and fracture energy variability, both in the transverse and longitudinal directions. This variability can be explained by the different outgrowth concentrations between the lower and upper parts of thuya burl. Thuya burl is less tough in TL system than in RL system due to the radial orientation of outgrowths from the centre to the outside of the burl. During the tests, it was noted that the parts on either side of the cut did not separate perfectly. The two arms frequently remained joined by twisted filaments.

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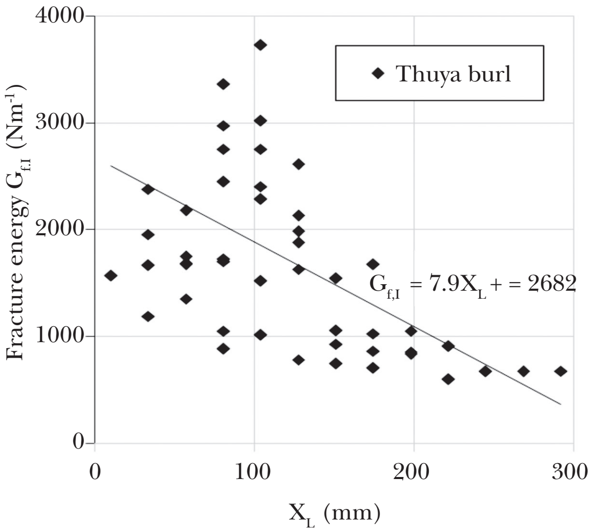
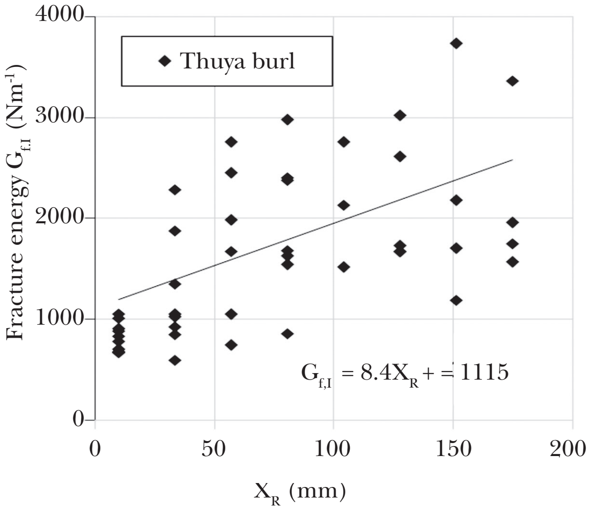


(a)



(b)

Figure 11 Fracture energy of thuya burl in RL system: variation along (a) L and (b) R directions

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